United States Department of the Interior

Geological Survey

Review of Lake Michigan Seismic Reflection Data

by

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Open File Report 80-902

1980

Prepared on behalf of the
OFFICE OF NUCLEAR REGULATORY RESEARCH,
UNITED STATES NUCLEAR REGULATORY COMMISSION

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

CONTENTS

ILLUSTRATIONS

Page

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ABSTRACT

Of 19,000 km of seismic reflection data for Lake Michigan, about 4,000 km penetrated to a depth that provided information about the bedrock underlying the lake.

The seismic data were used to identify the Paleozoic bedrock contacts underlying Lake Michigan and to extend under the lake the geologic contacts shown on King and Beikman's Geologic Map of the United States. Potential salt collapse features under the lake that could present geologic hazards to structures were identified. The western margin of the zone of possible collapse features extends from just offshore near Sheboygan, Wisconsin, northeastward to the Straits of Mackinac. The eastern margin of this zone extends from offshore near Sheboygan northeastward through Frankfort and Charlevoix, Michigan.

Introduction

Lake Michigan forms the western margin of the Michigan Basin (figs. 1 and 2). The lake (fig. 3) is divided into a northern and southern basin separated by a mid-lake topographic high that is a Middle and Upper Devonian (Traverse Group) cuesta. Northeast of the northern basin the bottom topography is rough, exhibiting a random ridge and valley topography. The lake was formed

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Figures 1, 2, & 3.--Near Here

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by a narrow glacial lobe of the continental glacier as it moved south parallel to the strike of the Paleozoic rocks that dip eastward into the Michigan Basin. The glacial erosion of these rocks has resulted in a relatively smooth, gently dipping lake floor in western Lake Michigan and a more rugged lake floor in eastern Lake Michigan. Dolomites of the Niagaran Series, which outcrop in eastern Wisconsin, form the base of the gently sloping western floor of the lake. A series of cuestas form the base to the more rugged eastern side of the lake. Overlying this Paleozoic surface is a series of glacial tills of the Wisconsinan Stage that are in turn overlain by late Quaternary glaciolacustrine and lacustrine sediments.

The current study reviews the various seismic investigations conducted in Lake Michigan (fig. 4) and reinterprets a 1968 single-channel seismic-reflection survey (Wolosin, 1972; Wold and Hutchinson, 1979). The major

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Figure 4.--Near Here

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objective of this review was to locate possible areas where potential salt collapse structures might occur. These structures have been observed in the

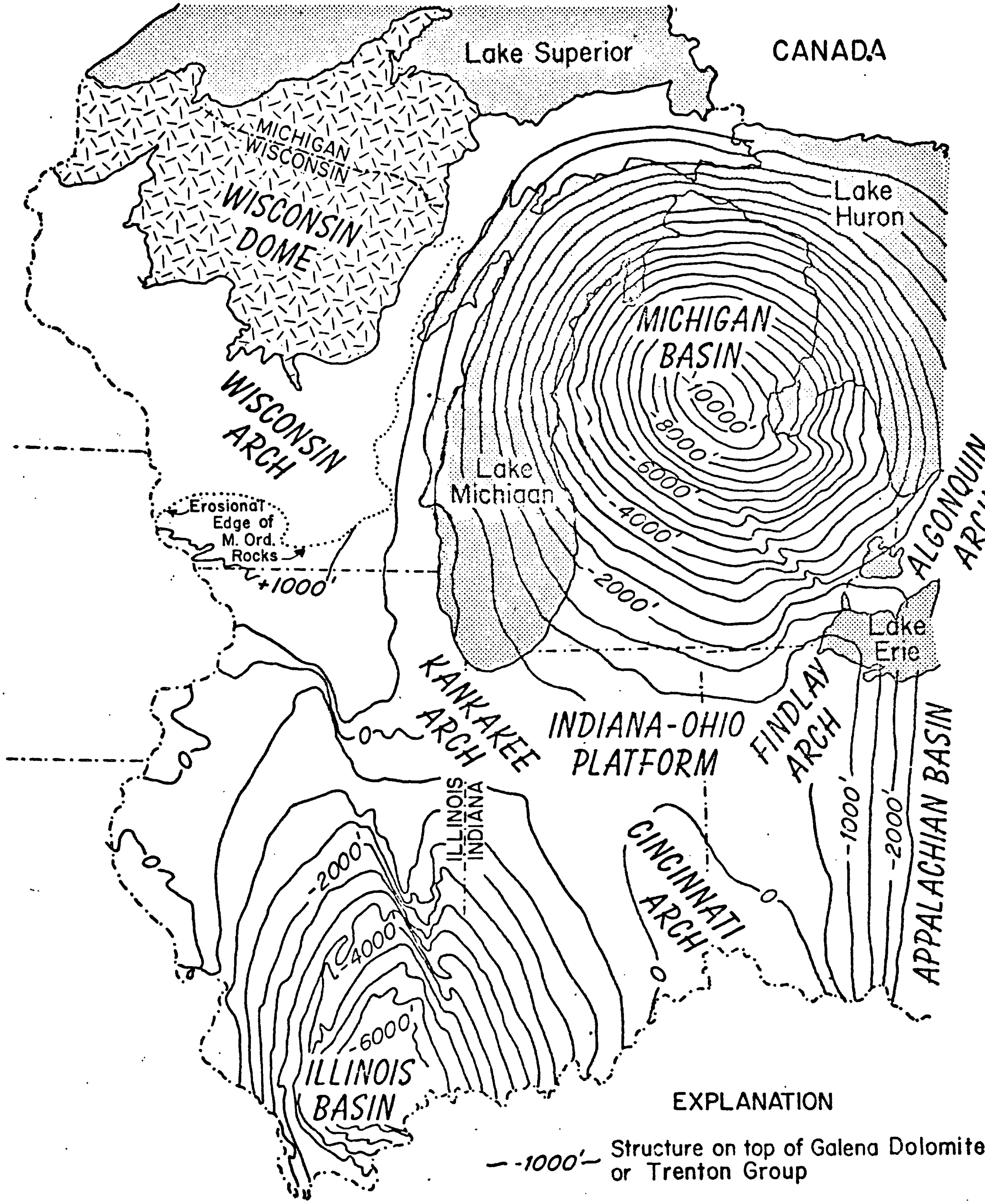

Figure 1.--Regional structure modified from Tectonic Map of the United States (Cohee, 1961).

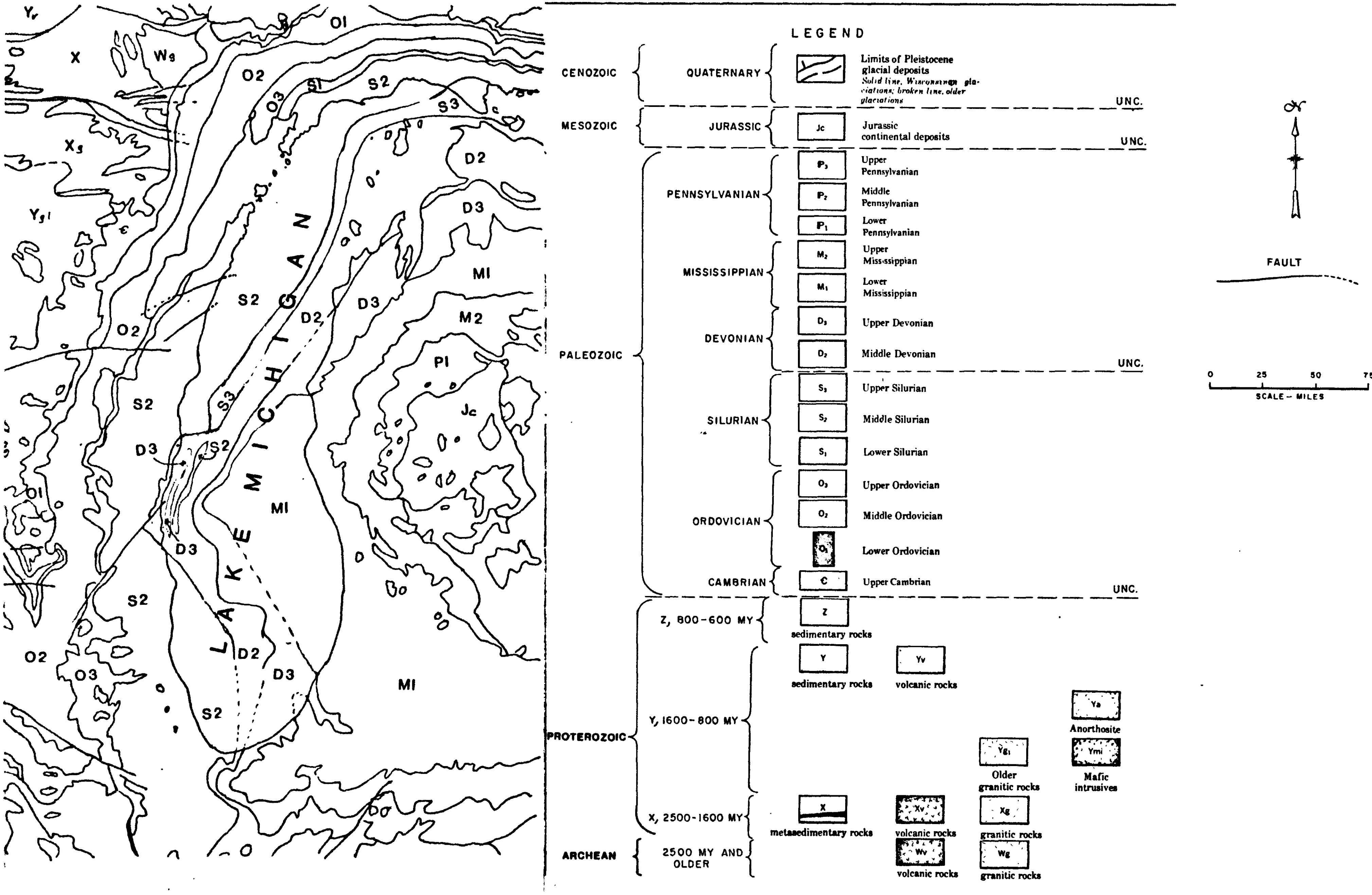

Figure 2.--Geologic Map of the Lake Michigan area modified from Geologic Map of the United States (King and Beikman, 1974).

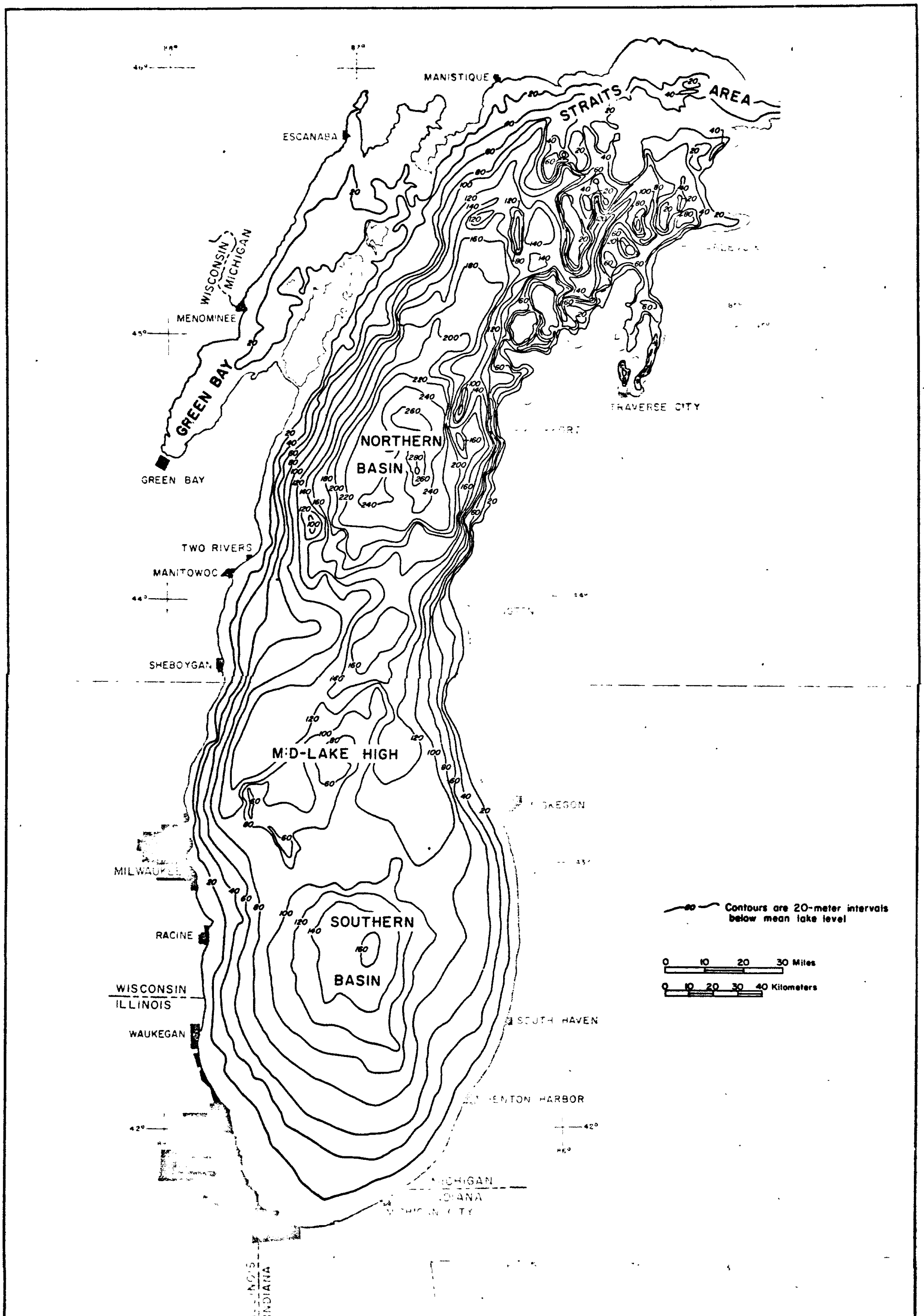

Figure 3.--Bathymetry Map of Lake Michigan (Wickham and others, 1978).

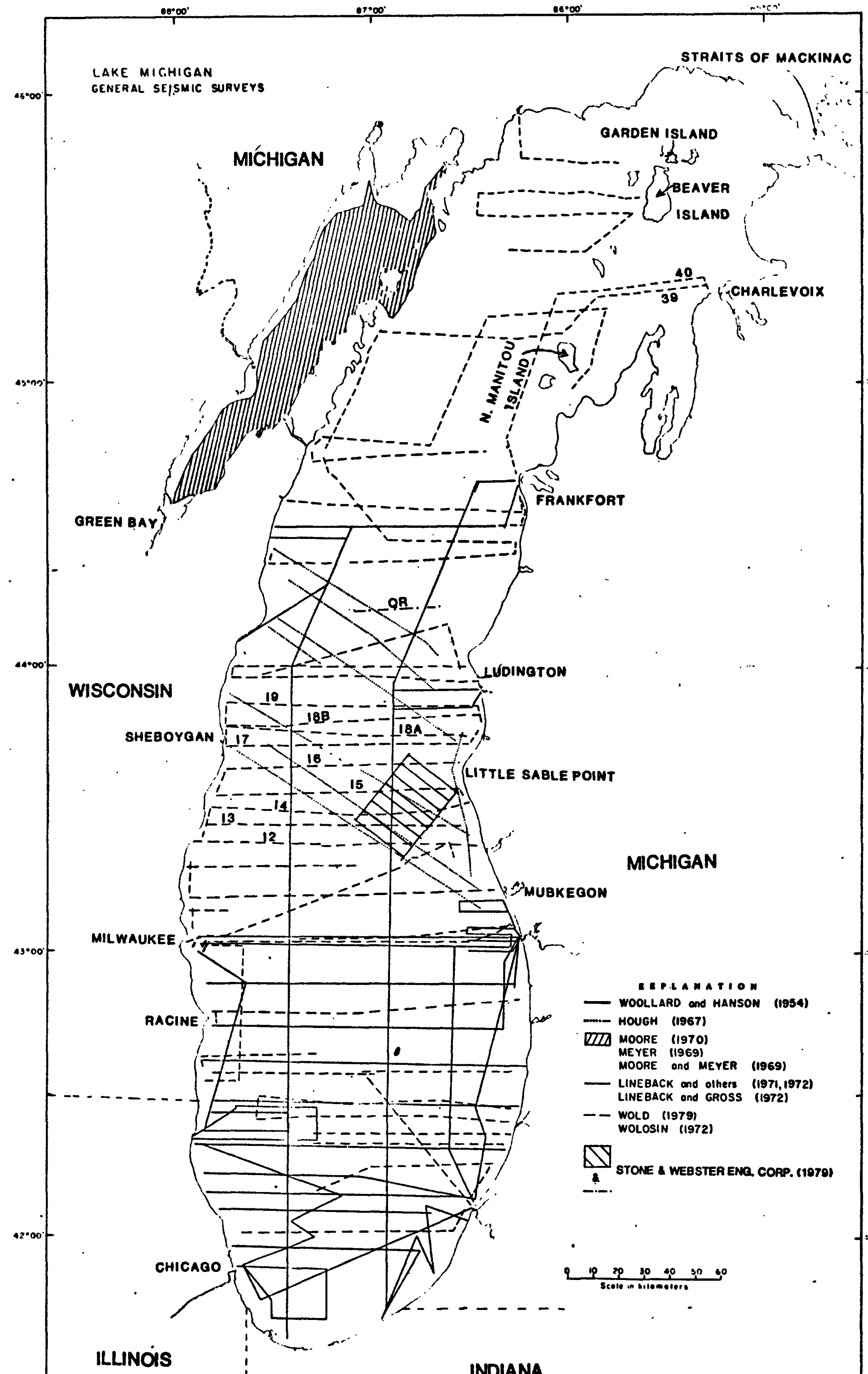

Figure 4.--Location map showing track lines for seismic surveys of Lake Michigan.

Straits of Mackinac and appear to be associated with the Mackinac Breccia (see fig. 5). The brecciated zone seems to involve all of the formations

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Figure 5. Near Here

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between the Niagaran Series (Middle Silurian) and Dundee Limestone (Middle Devonian) (Hough, 1958). Apparent leaching of the salt in the Salina Group (Upper Silurian), which overlies the Niagaran Series, has resulted in the formations older than Dundee Limestone, being broken and eroded. These zones of collapse may pose potential hazards to manmade structures and therefore are of interest. The main goal of this study was to locate the Salina - Niagaran contact (Middle-Upper Silurian boundary) and the Middle-Upper Devonian boundary, because the formations between these two boundaries contain the rocks most likely to exhibit collapse structures.

Seismic-Reflection Investigations

A number of seismic studies of Lade Michigan have been carried out. However, the bulk of these seismic data are single-channel high resolution. As used in this discussion, a "high-resolution" CDP seismic survey is one in which the maximum recording time is limited to one second of penetration. This is in contrast to a "high-resolution" single-channel seismic survey that normally uses a seismic energy source with a frequency ranging between 3.5 KHz and 14.5 KHz and has a penetration into the subbottom limited to approximately .125 second.

The first sub-bottom seismic reflection investigations of Lake Michigan were reported on by Hough (1967), as part of a bedrock framework study of Lake Michigan. The study utilized dredge samples, 700 km of seismic profiles, and short core samples. The single-channel seismic data were obtained with a sparker as an energy source which provided limited sub-bottom penetration. In

					WISCONSIN OUTCROP NOMENCLATURE		MICHIGAN OUTCROP NOMENCLATURE	
GEOLOGIC TIME			TIME-STRATIGRAPHIC		ROCK-STRATIGRAPHIC			
ERA	PERIOD	EPOCH	SYSTEM	SERIES	GROUP	FORMATION	GROUP	FORMATION
PALEOZOIC	MISSISSIPPIAN-DEVONIAN Unassigned							
	DEVONIAN	UPPER D3	DEVONIAN			Antrim		Ellsworth Sh. (Western Michigan)
				CHAUTAUQUAN				Antrim Sh.
				SENECAN		Milwaukee	TRAVERSE	Squaw Bay Ls.
		MIDDLE D2		ERIAN				Thunder Bay Ls.
								Potter Farm Fm.
								Norway Point Fm.
								Four Mile Dam Fm.
						? ?		Alpena Ls.
						Thiensville		Newton Creek Ls.
								Genshaw Fm.
								Ferron Point Fm.
								Rockport Quarry Ls.
								Bell Sh.
								Rogers City Ls.
						? ?		Dundee Ls.
				ULSTERIAN		Lake Church	DETROIT RIVER / MACKINAC BRECCIA	Anderdon Fm.
								Lucas Fm.
								Amherstburg Fm.
								Sylvania Ss.
								Bois Blanc Fm.
								Garden Island Fm.
	SILURIAN	UPPER S3	SILURIAN	CAYUGAN			BASS ISLANDS	Raisin River Dol.
								Put-in-Bay Dol.
							SALINA	St. Ignace Dol. (No Penin.)
						Waubakee		Pte. aux Chenes Sh.
		MIDDLE S2		NIAGARAN		Racine		Engadine Dol.
						Manistique	MANISTIQUE	Cordell Dol.
								Schoolcraft Dol.
						Hendricks	BURNT BLUFF	Hendricks Dol.
						Byron		Byron Dol
								Lime Island Dol
		LOWER S1		ALEXANDRIAN		Mayville	CATARACT	Cabot Head Sh.
								Manitoulin Dol.

Figure 5.--Regional stratigraphic column modified from Stone & Webster Engineering Corp. (1979).

order to study bedrock outcrops, dredge samples were taken from steep or near vertical cliffs.

In 1968 a much more comprehensive seismic-reflection survey was carried out by the author in conjunction with a surface-gravity study of Lake Michigan. In this survey some 3700 km of single-channel 10 in.^{3} airgun data were obtained that provided extensive information on the Paleozoic bedrock surface. These were partially reported on by Wolosin (1972).

In 1968 and 1969 detailed high-resolution seismic surveys (3.5 KHz) of Green Bay were carried out and reported on by Moore and Meyer (1969), Meyer (1969), and Moore (1970). These studies were a combination of 7 KHz high-resolution seismics and extensive coring and bottom sampling. The studies were mainly concerned with the sediment structure, composition, and mineral resources. Little information on the bedrock was obtained from this work.

In 1970 a seismic survey of Southern Lake Michigan was started by the Illinois State Geological Survey in cooperation with the University of Wisconsin - Madison, and by 1972 some 3000 km of high-resolution (3.5 KHz and/or 7 KHz) single-channel seismic data were obtained. This work has resulted in a variety of publications (Lineback and others, 1971, 1972, 1974; Lineback and Gross, 1972) on southern Lake Michigan sediments, their structure, and composition, and the bedrock surface. The investigations have involved an extensive bottom coring and sampling program combined with 3.5 KHz/7 KHz high-resolution seismic profiling. These studies (Lineback and others, 1974) defined four glacial till units under Lake Michigan south of Frankfort, Mich. The work also differentiated glaciolacustrine and lacustrine sediments in this area.

In 1971 some 950 km of proprietary 12-fold CDP seismic data were obtained by Dresser Olympic for hydrocarbon exploration in Lake Michigan but it is of little value to this review because the results are not available. In 1979 high-resolution 12-channel CDP seismic studies were done for the Wisconsin Utilities Haven Nuclear Plant (Stone & Webster Engineering Corporation 1979) as part of an overall geologic study in an area near Sheboygan, Wisconsin and in a small area in east central Lake Michigan near latitude $43^{\circ}30'$ N. This survey obtained some 670 km of data. When these high-resolution CDP seismic data are used in conjunction with the much more extensive 10 in.^{3} airgun data obtained in 1968, the CDP data can provide a means of control for interpreting the single-channel airgun data by providing a more positive identification of which reflections indicate Paleozoic bedrock, till, or lacustrine sediments.

An additional 7200 km of high-resolution seismic data (mainly 14.25 KHz) were obtained by Wickham and others (1978). The bulk of the data provides an excellent means of identifying the areal and vertical distribution of the glaciolacustrine and lacustrine sediments in Lake Michigan.

In summary, the only seismic data that provide extensive information on the Paleozoic bedrock are the 10 in.^{3} airgun data and the proprietary CDP data that are unavailable and restricted in areal coverage. In addition, some bedrock information was obtained in the survey by Lineback and others, 1971. The track lines for all of the seismic data, with the exception of the proprietary CDP data, are shown in figure 4. Three depth-to-bedrock maps have been published as a result of these studies of various sections of the lake (Wolosin, 1972; Stone & Webster Engineering Corporation, 1979; Lineback and others, 1971). The Wolosin (1972) map covers the central part of the lake between 43° and 44° latitude. This map assumed a velocity of 1520 m/sec for the unconsolidated sediments (till and lacustrine sediments). With the velocity information now available from the CDP survey of Stone & Webster Engineering Corporation (1979), it is apparent that 1520 m/sec is too low, which would lead to a depth to bedrock map that is too shallow. Stone and

Webster Engineering Corporation (1979) modified the Wolosin depth-to-bedrock map slightly and extended it northward to about $44^{o}30'$ N latitude. The map of Lineback and others (1971) shows the Paleozoic bedrock surface south of latitude 43^{o}. This map like the Wolosin map used an average velocity that was too low and therefore gave a map with depths that are too shallow.

Discussion

The 1968 10 in^3. single-channel airgun data were obtained as part of a gravity study of Lake Michigan. The seismic equipment was operated on a non-interference basis with the shipboard gravimeter, obtaining about 3700 km of data (fig. 4).

A series of nine consecutive east-west seismic profiles obtained in the central part of the lake were selected from the survey (no. 12 through 19, fig. 4) and are shown in figures 6 through 17. The line drawings in the lower part of each figure help to illustrate the subsurface seismic stratigraphy. The

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Figures 6 through 17.--Near Here

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top line represents the water bottom and the heavy line in the subsurface is the interpreted bedrock surface. The lines below the heavy line represent

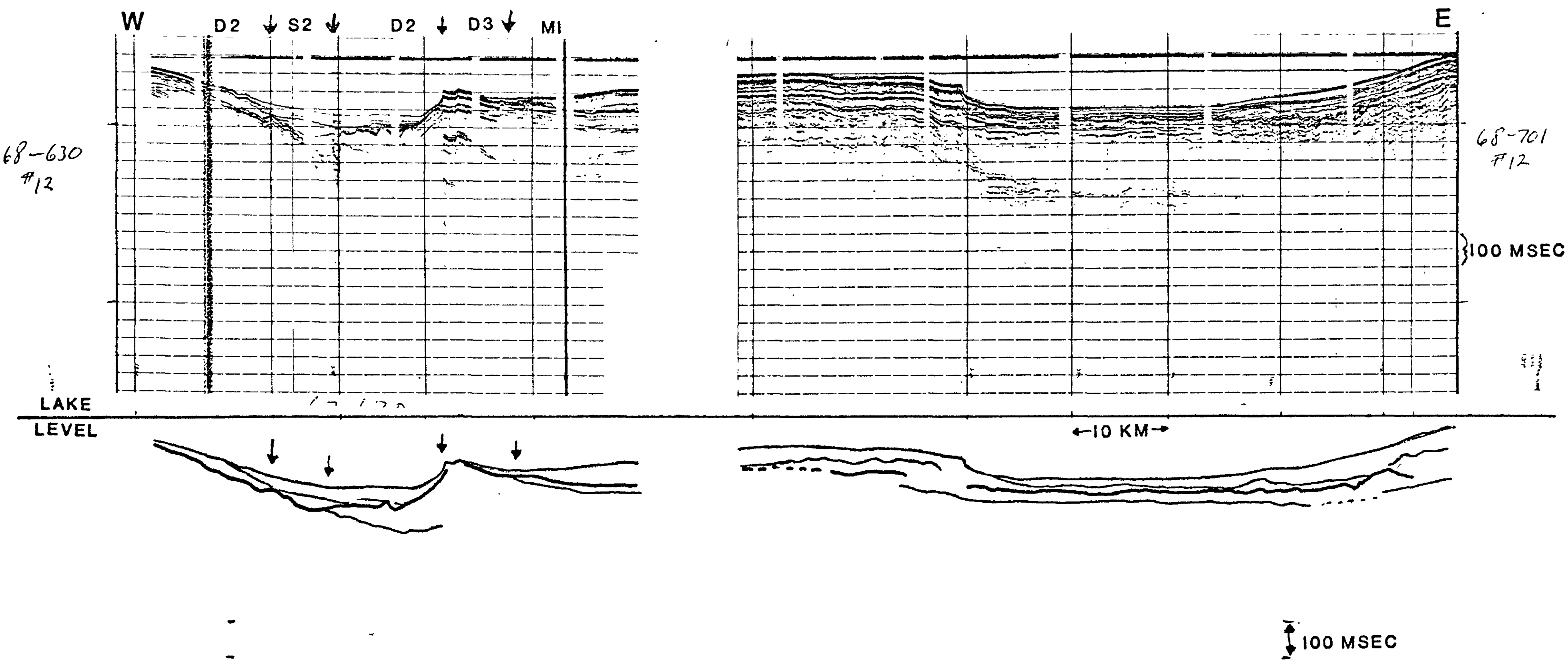

Figure 6.--East-west seismic profile 12 (see fig. 4). Heavy line is the bedrock surface and the lines below the heavy line represent reflectors within the bedrock. The symbols D_2, D_3, and M along the top of the profile refer to the rock units shown in figure 4. The vertical arrows along the top are contacts between the different stratigraphic units.

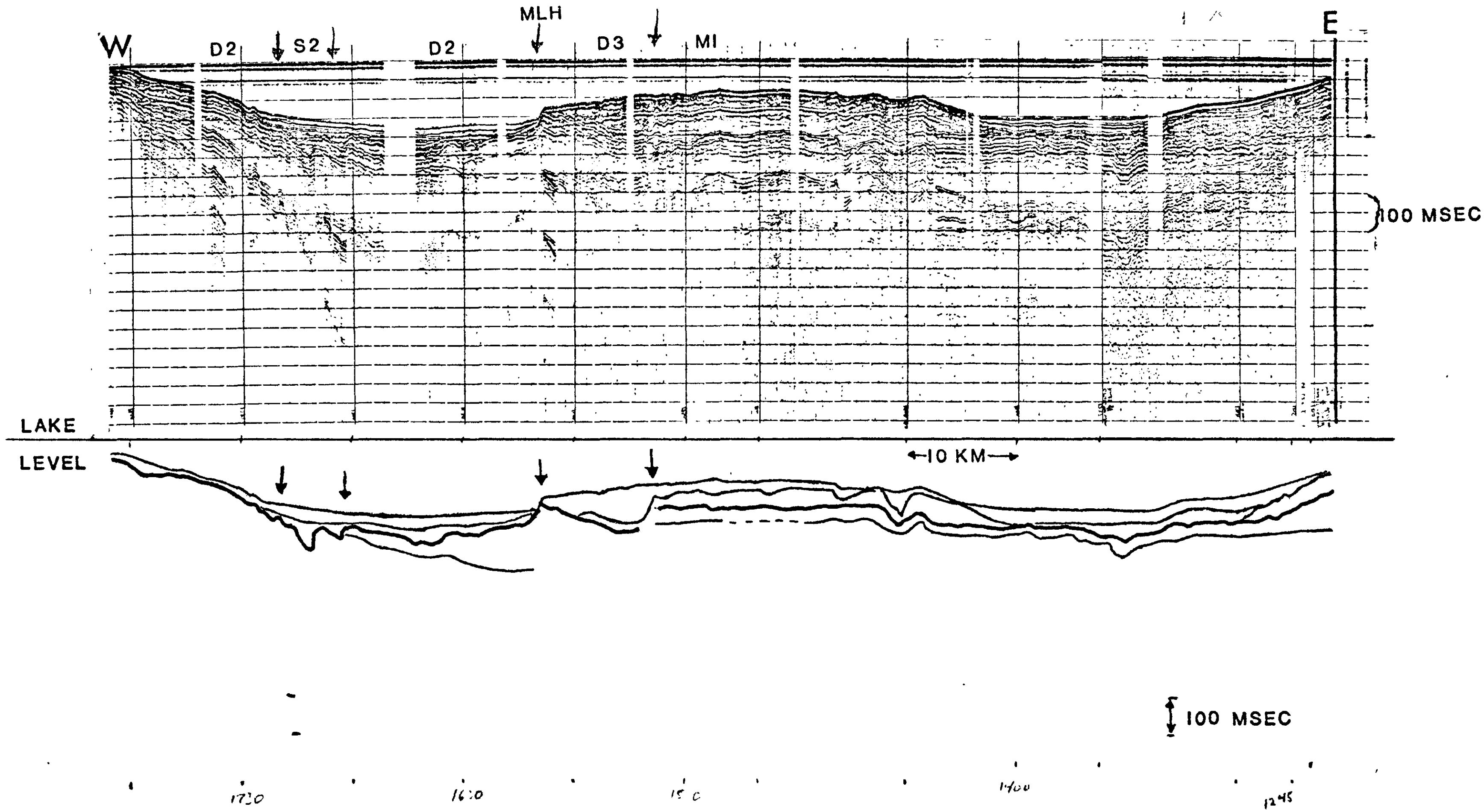

Figure 7.--East-west seismic profile 13 (see fig. 4). The symbols are the same as in figure 6 with the addition of the vertical arrow showing the location of the Mid-Lake High (MLH).

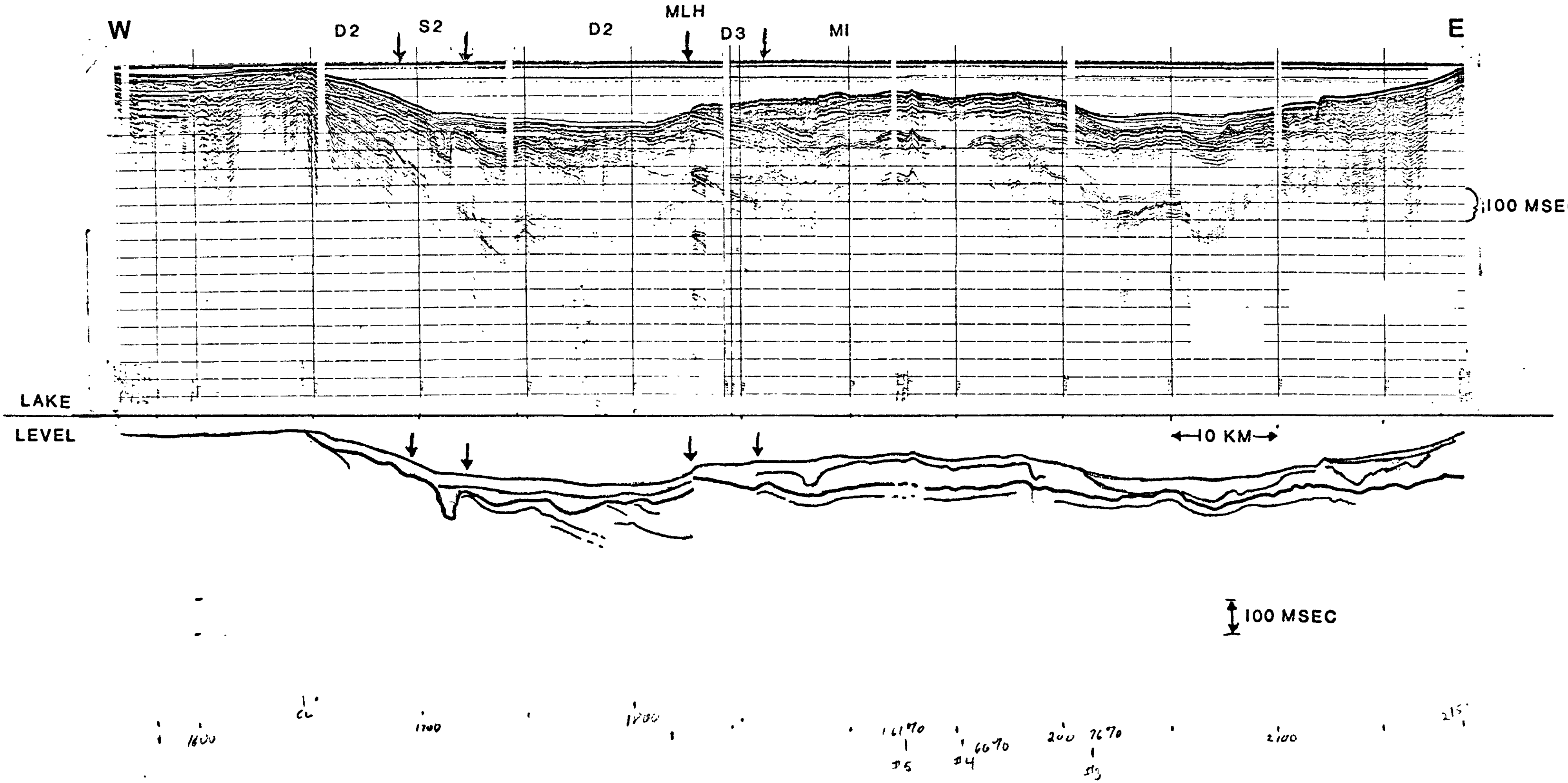

Figure 8.--East-west seismic profile 14 (see fig. 4). The symbols are the same as in figures 6 and 7.

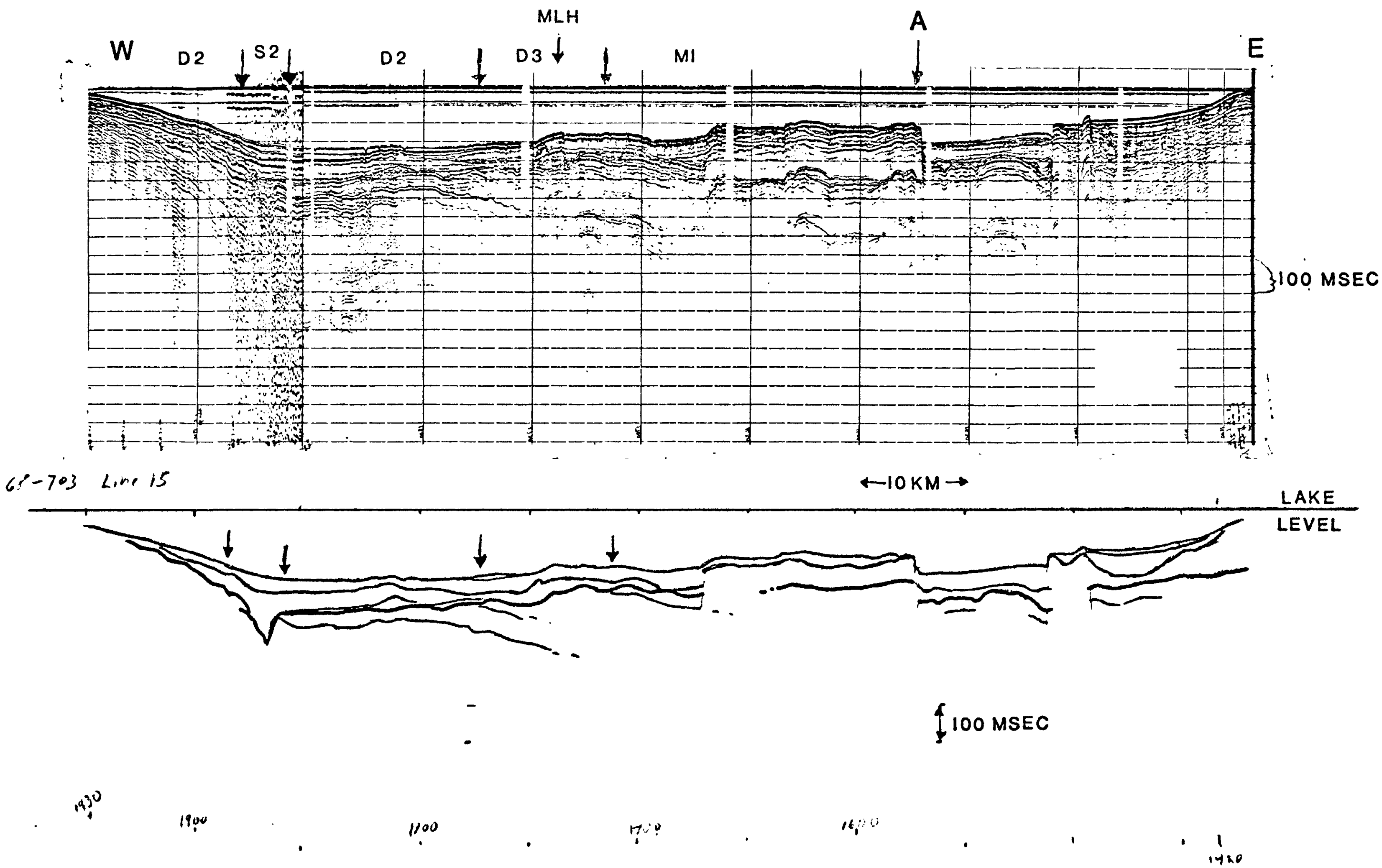

Figure 9.--East-west seismic profile 15 (see fig. 4). The symbols are the same as in figures 6 and 7. Point A is referred to in the text, page 31.

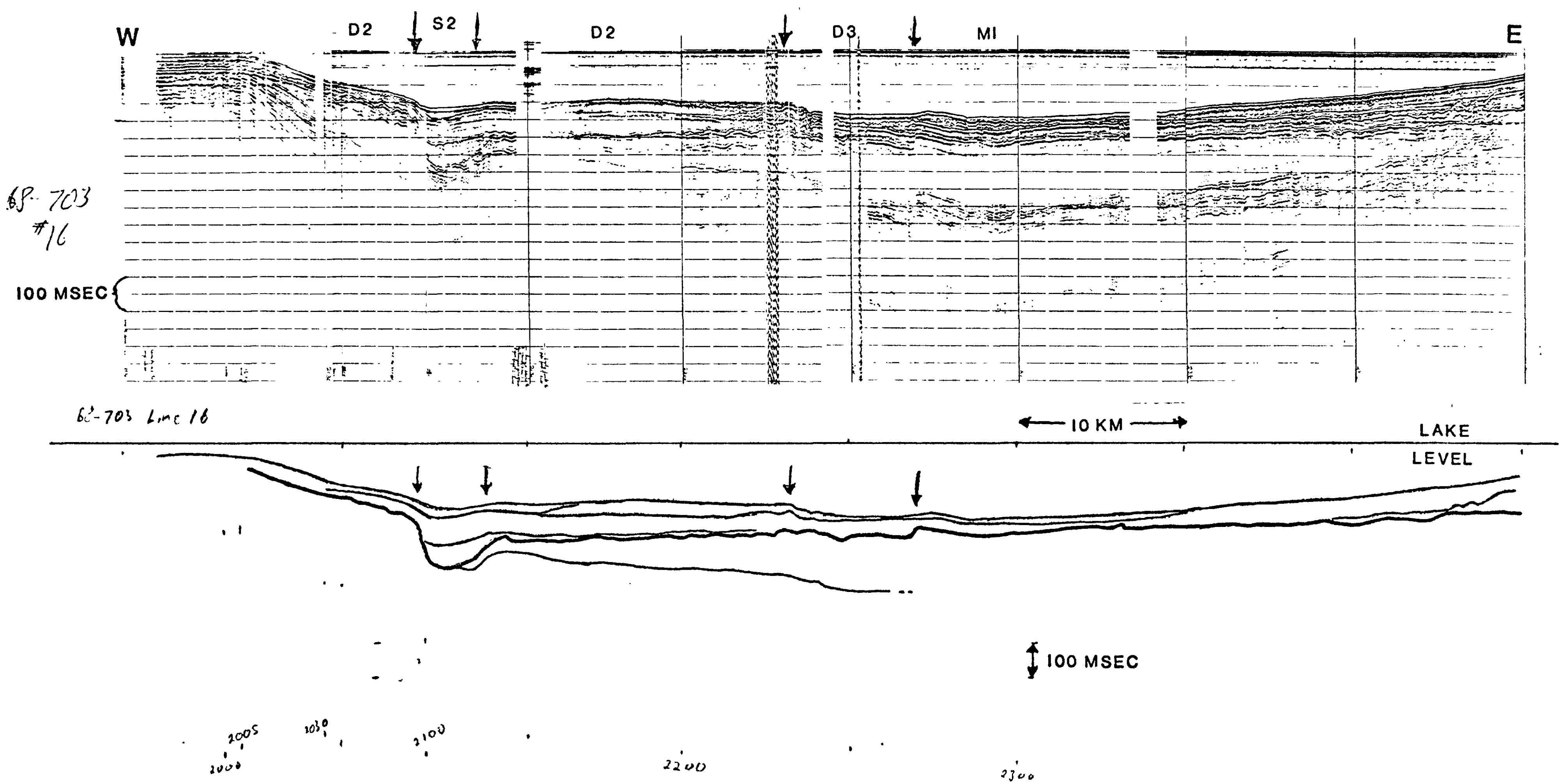

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Figure 10.--East-west seismic profile 16 (see fig. 4). The symbols are the same as in figure 6.

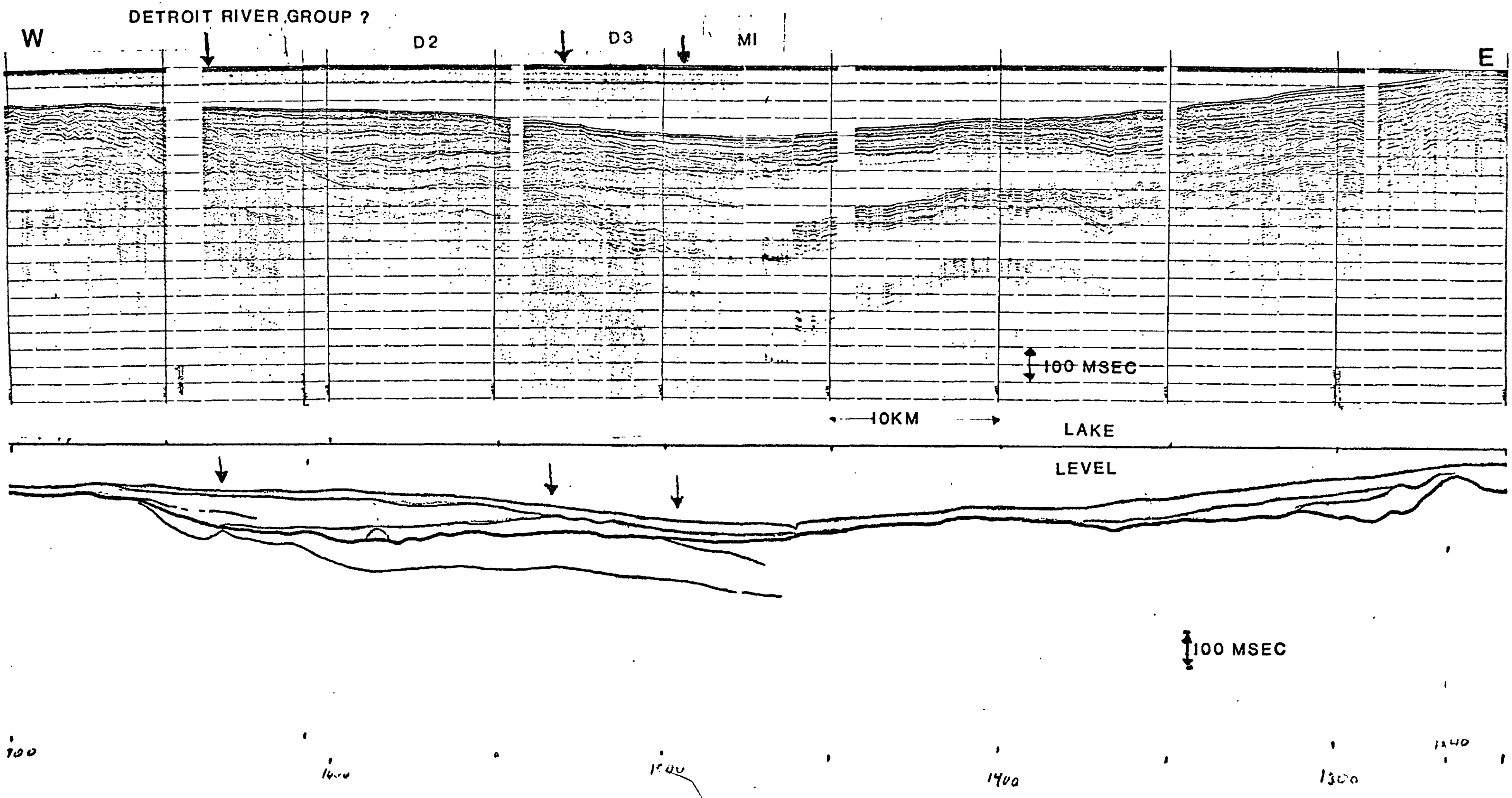

Figure 11.--East-west seismic profile 17 (see fig. 4). The symbols are the same as in figure 6.

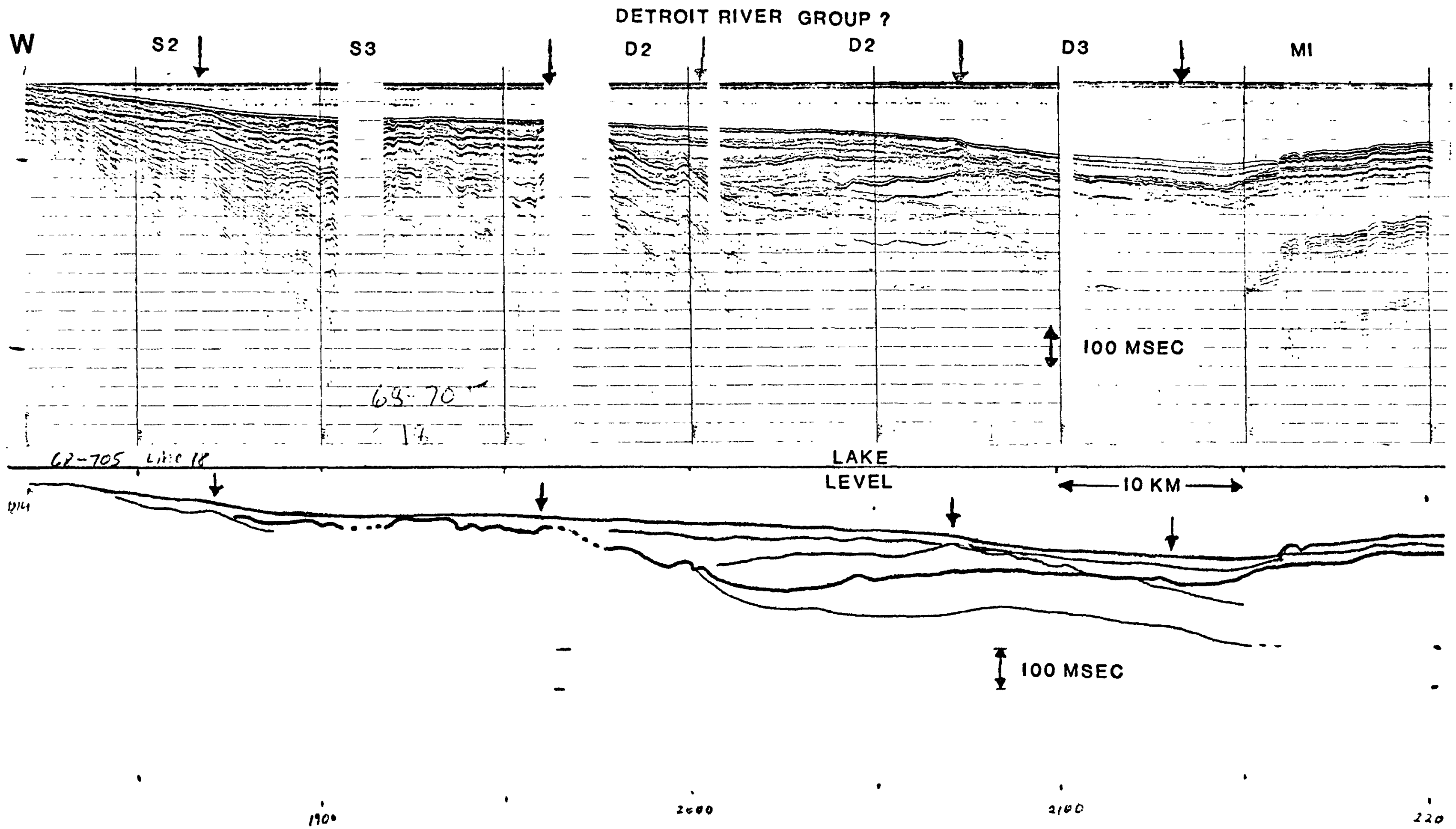

Figure 12.--Western part of east-west seismic profile 18A (see fig. 4). The symbols are the same as in figure 6.

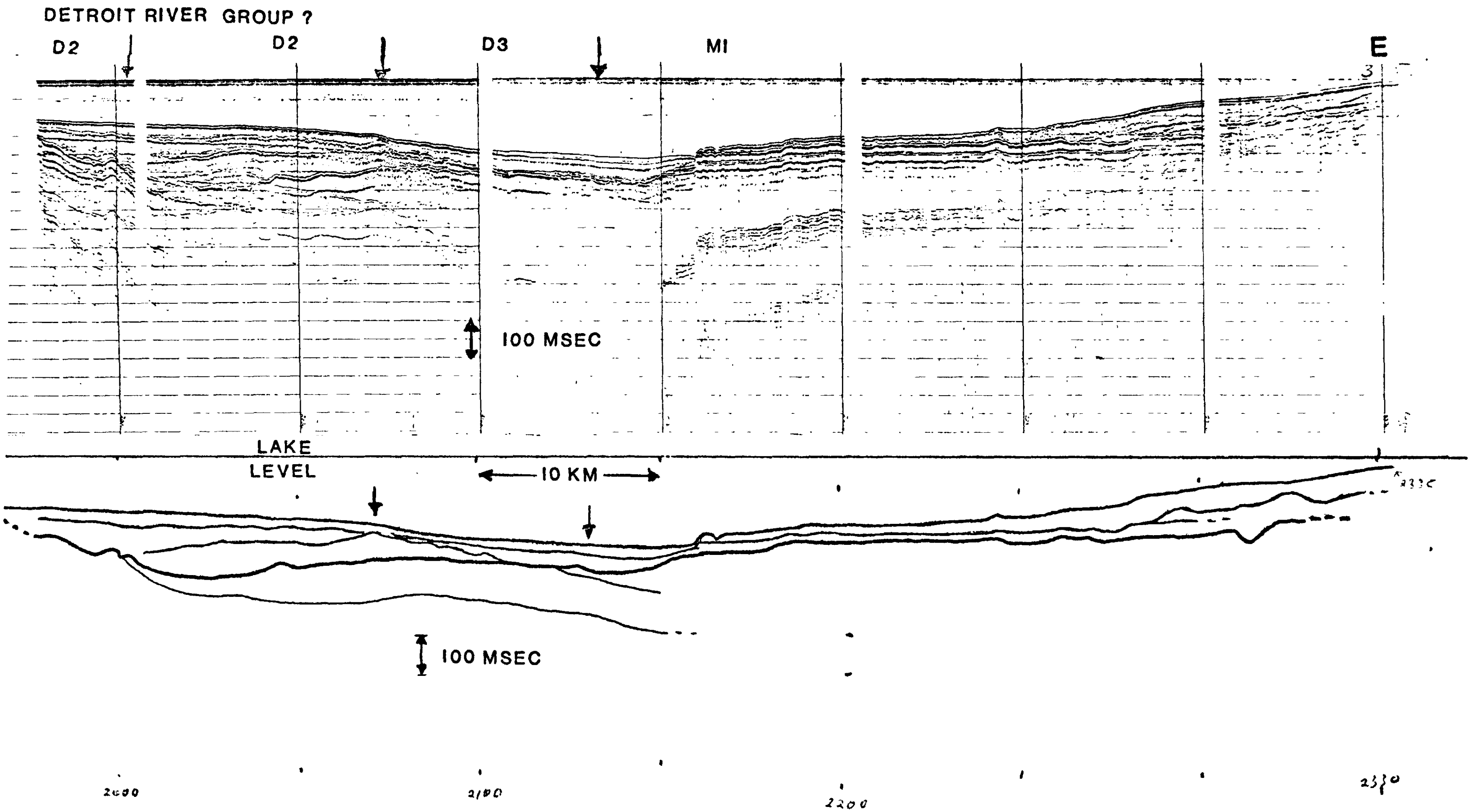

Figure 13.--Eastern part of east-west seismic profile 18A (see fig. 4). The symbols are the same as in figure 6.

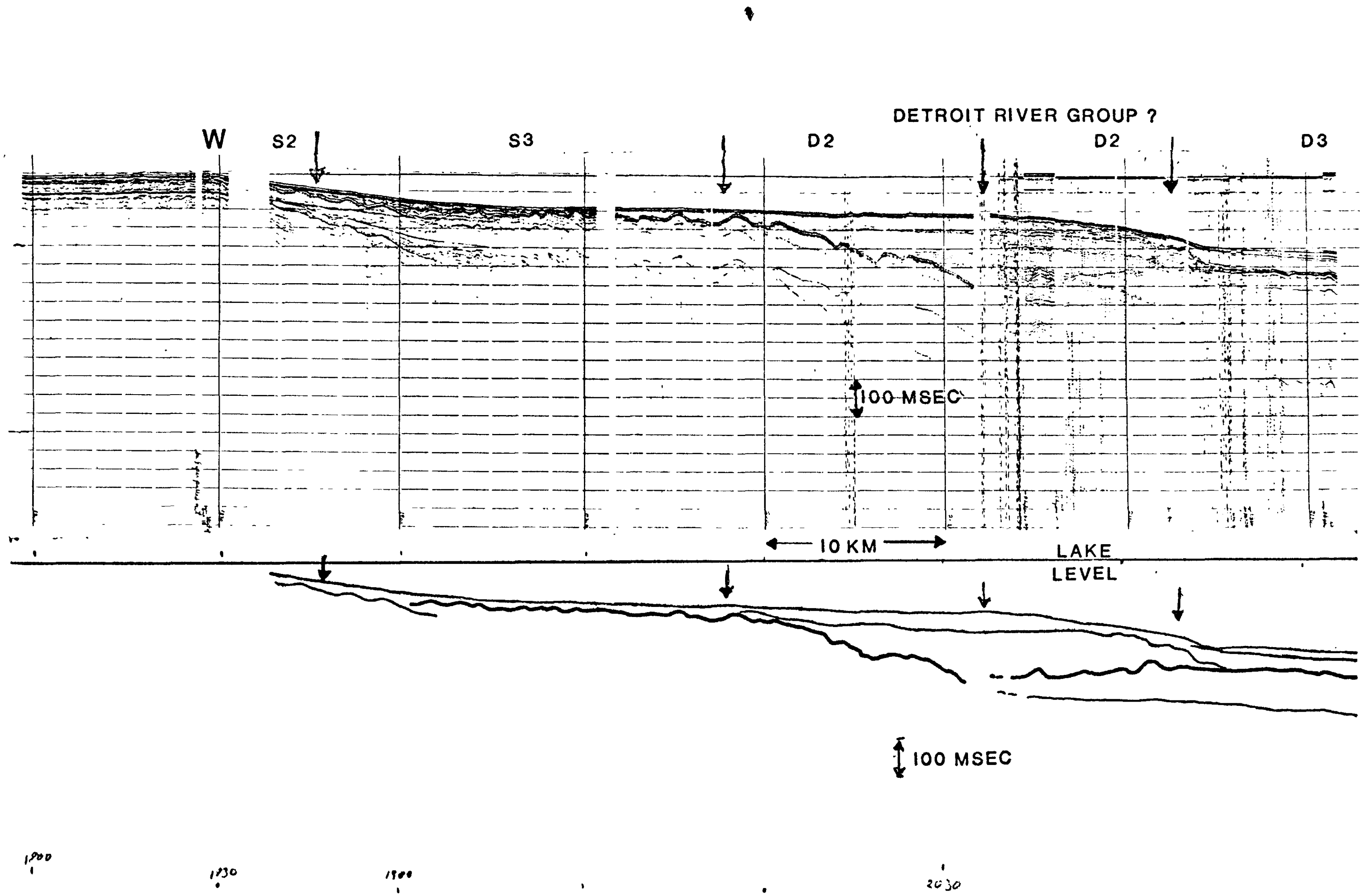

Figure 14.--Western part of east-west seismic profile 18B (see fig. 4). The symbols are the same as in figure 6.

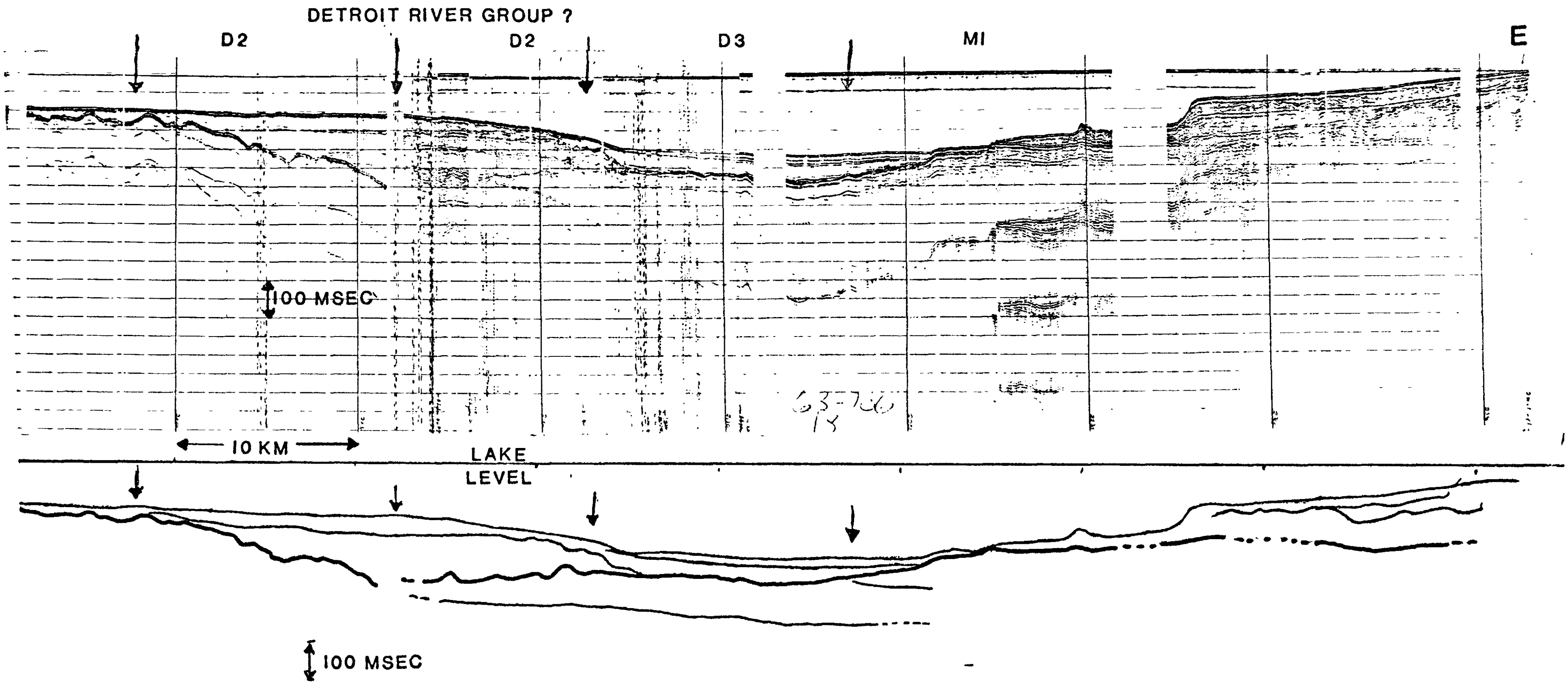

Figure 15.--Eastern part of east-west seismic profile 18B (see fig. 4). The symbols are the same as in figure 6.

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19

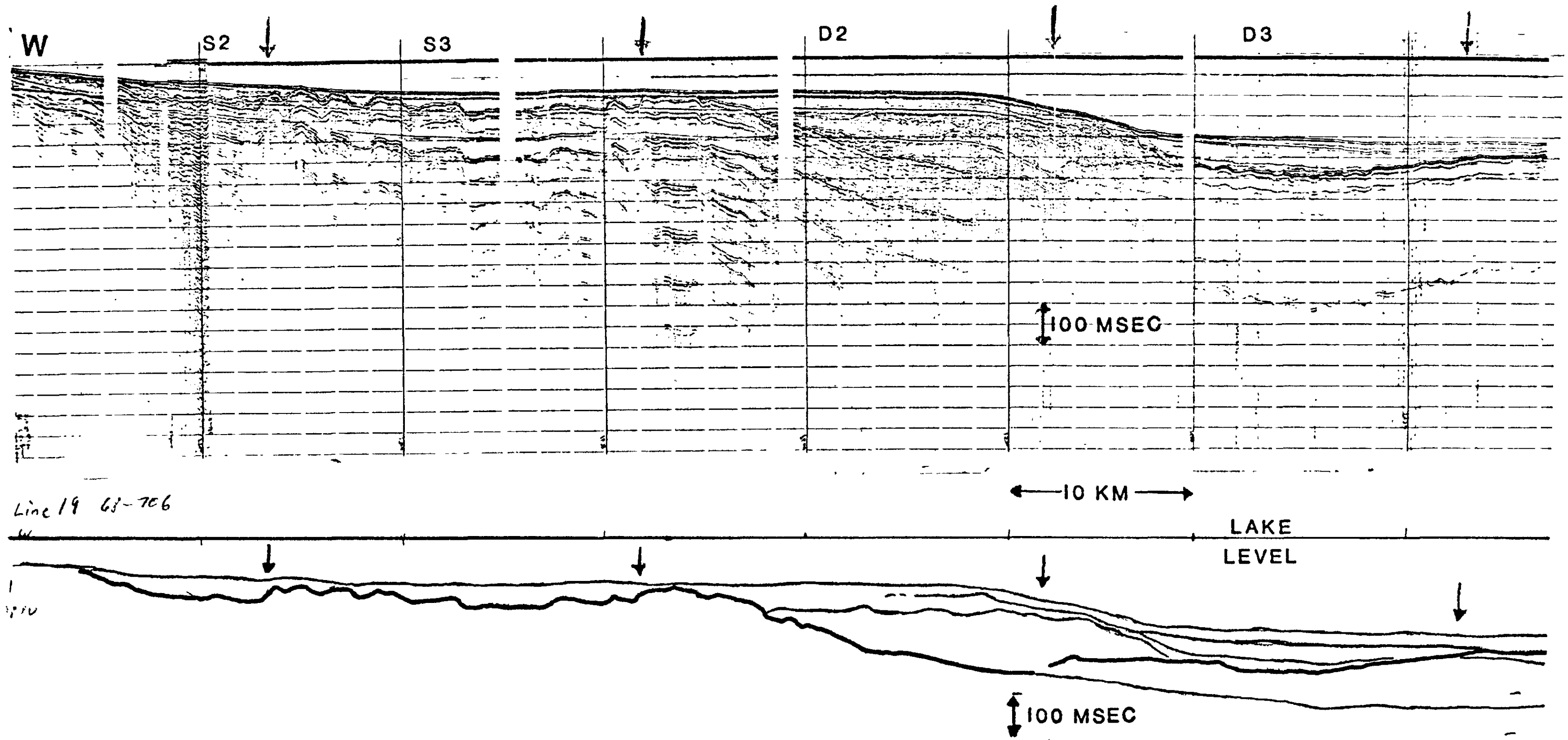

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Figure 16.--Western part of east-west seismic profile 19 (see fig. 4). The symbols are the same as in figure 6.

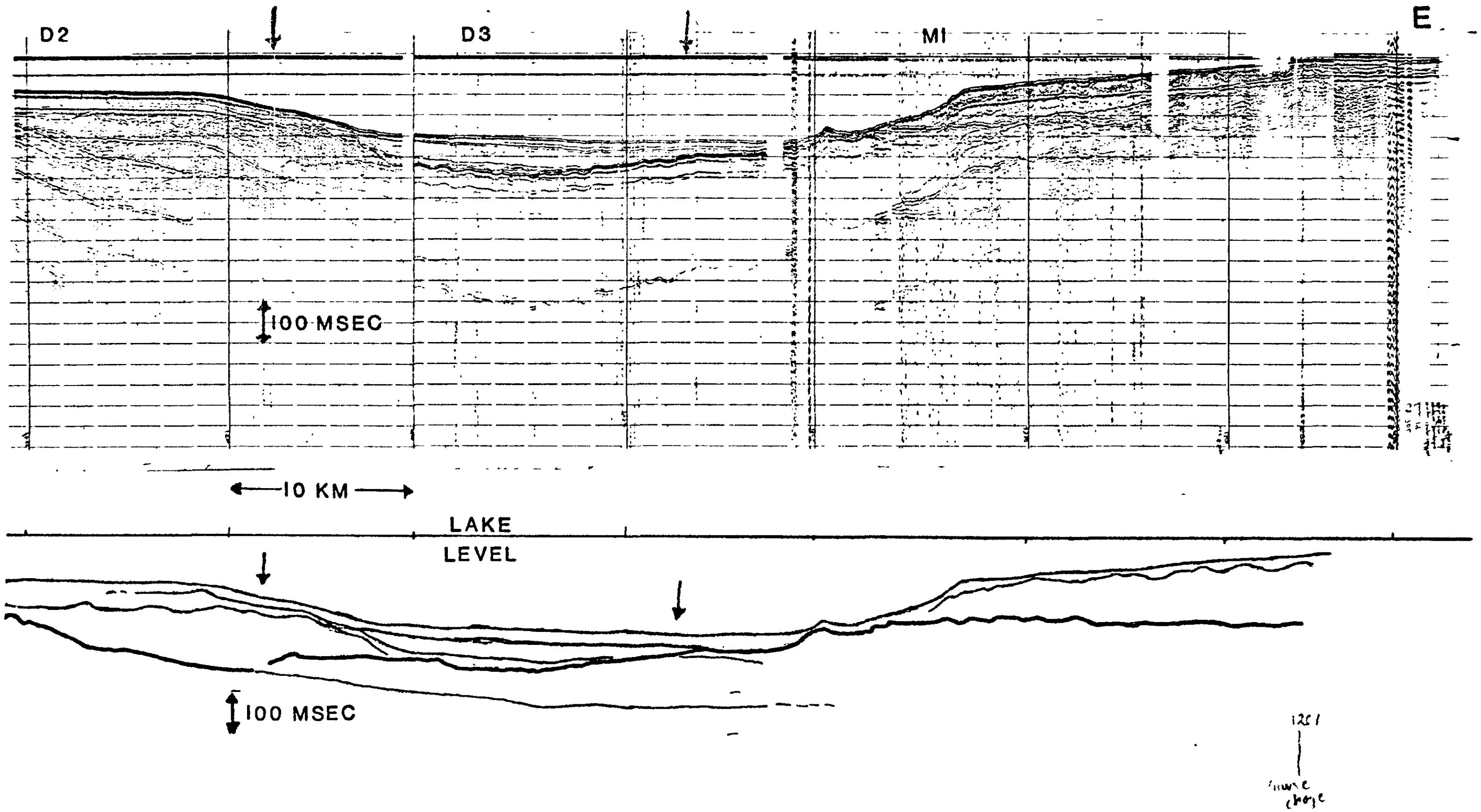

Figure 17.--Eastern part of east-west seismic profile 19 (see fig. 4). The symbols are the same as in figure 6.

prominent reflectors within the Paleozoic bedrock. Lines above the heavy line represent prominent reflectors within the unconsolidated sediments. The location of the major interpreted Paleozoic bedrock contacts are shown along the top of the observed seismic profile. Bedrock contact, as used here, refers to the contact between epochs of the periods of the Paleozoic Era (see figs. 2 and 5). For example, an S_2S_3 contact represents the Middle-Upper Silurian contact which under Lake Michigan, is the Niagaran series - Salina Group contact. The depths are determined by multiplying the two-way travel time (shown on the records) by half the assumed velocity.

The seismic records in figures 16 and 17 illustrate several features observed in the seismic data. The lake bottom slope is smoother on the west than on the east. On the left half of the record in figure 16 an irregular bedrock surface overlain by a thin cover of glacial till and lacustrine sediments is identified resulting in strong multiples that interfere with the seismic reflections. The bedrock surface shows a cuestalike feature often associated with Paleozoic bedrock contacts; in this case the S_3D_2 contact. These patterns can be traced from profile to profile (see S_3D_2 contact, figs. 12, 14, and 16). Figure 18 diagrammatically illustrates the bedrock contact interpretation of the basement topography. Basically scarps form on the resistant beds resulting in cuestas that are interpreted as shown in figure 18. When the unconsolidated sediments and till units are thicker and the

Figure 18.--Near Here

water depths greater, the travel times of multiples are much larger and it is often possible to trace the contact between bedrock formations as they dip

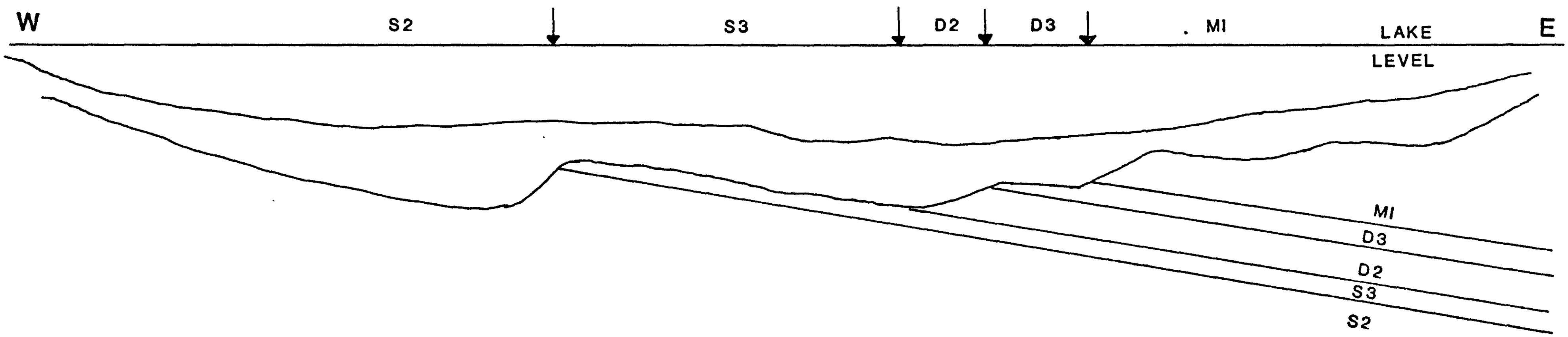

Figure 18.--Example of bedrock contact interpretation.

to the east. In the case of the profiles shown in figures 16 and 17, the D_2D_3 contact can be traced for about 25 km to the east before the weak reflection crosses the bottom multiple and is lost.

South of an east-west line passing just north of Milwaukee, the sedimentary accumulation is thin with the exception of a few small isolated areas. The eastern side of the lake, at least as far north as Frankfort, tends to show much higher accumulations of sediments than the western side of the lake (see figs. 14-17). The area north and east of North Manitou Island (see figure 4, northern end of lake) is lacking in seismic data. However, the data that are available seem to indicate only minor amounts of sediments except for narrow troughs in the ridge and valley topography, characteristic of that section of the lake.

The objective of the data review was to identify those areas where the Mackinac Breccia might occur, the zone between the S_2S_3 contact and the D_2D_3 contact. Since it is the effect of leaching in the Salina (in S_3) that is the cause of the Mackinac Breccia, the area of interest would therefore only include those areas above S_3. That eliminates areas south of Sheboygan because figure 19 shows S_3 to be pinched out south of that point.

Figure 19.--Near Here

The S_2S_3 contact (fig. 19) is the contact between the Middle and Upper Silurian. The Middle Silurian, S_2, is represented by the Niagaran Series and the Salina Group is part of the Upper Silurian, S_3. In the area west of Beaver Island, the S_2S_3 contact has been identified on the four east-west seismic profiles as a point where the subsurface topography to the east is rough and to the west the topography is relatively smooth. The alignment

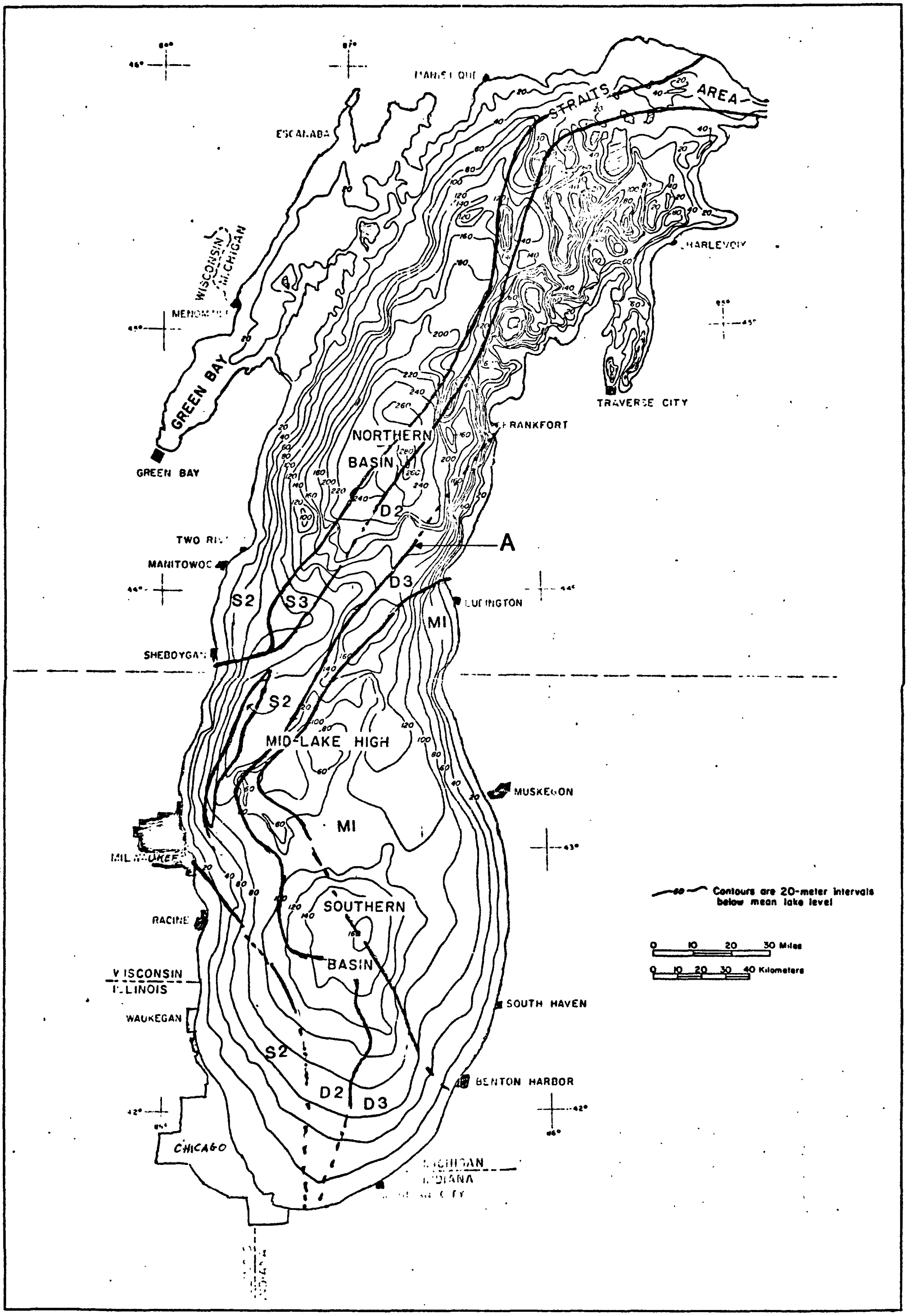

Figure 19.--Map showing basement rock outcrops in Lake Michigan. Bathymetry from Wickham and others (1978).

between profiles is good and the extension of the S_2S_3 contact east to the shoreline north of the Straits of Mackinac (north end of the lake) parallels the S_1S_2 contact shown on the Geologic Map of the U.S. (King and Beikman, 1974) (see fig. 2). The S_2S_3 contact continues southward from Beaver Island (see fig. 4, northern part of lake) following the most westerly major cuesta-like features in the subsurface. This contact can be traced southwesterly (figs. 12, 14, 16) to Sheboygan, Wisconsin, where it comes onshore as the S_2D_2 contact.

The S_3D_2 contact (fig. 19) passes just north of the Straits of Mackinac, westward through Garden Island (fig. 4, north end of lake), then turns southwestward where it crosses the four seismic profiles west of Beaver Island. This contact is identified on these profiles as the first major cuestalike feature in the subsurface to the east of the S_2S_3 contact. It passes southwestward about 8 km west of North Manitou Island and crosses the shoreline just south of Sheboygan, Wisconsin as the S_2D_2 contact (figs. 12, 14, 16). Since the S_2S_3 contact and the S_3D_2 contact both come onshore as the S_2D_2 contact, the Salina Group (in the Upper Silurian, S_3) appears to pinch out east of Sheboygan. Other major contacts recognized in figure 19 are the D_2D_3 and D_3M_1. The D_2D_3 contact in the central part of the lake occurs along a major topographic feature that is a westerly facing near-vertical cliff (figs. 6-9), the mid-lake topographic high. The D_3M_1 contact is identified in the subsurface as a distinct eastward-dipping bedrock reflector (figs. 6-13).

An exposure of Middle Silurian (S_2) is correlated with a valley cut into the subsurface paralleling the shore from about 10 km east of Milwaukee to a point about 18 km east of Sheboygan (figs. 6-10). A prominent northeast - trending bedrock reflection 35 km east of Sheboygan can be traced over a distance of 30 km (figs. 11-15). This may be the Detroit River Group (Middle Devonian, D_2).

The only contact that can be traced south of Milwaukee is the D_2D_3, and even then the correlations are tenuous. The correlations are based upon a prominent bedrock reflection which can be identified on all of the east-west profiles from Racine, Wisconsin, south.

Hough (1967) obtained dredge samples from the vertical cliffs in Lake Michigan. The bedrock units he identified from these samples fit the pattern for the bedrock contacts as they are plotted in figure 19, with two exceptions. These are two Ellsworth Shale samples found about 14 km and 37 km west of the D_2D_3 contact (Point A in fig. 19). These samples lie in the areas where the Middle Devonian (D_2) and Upper Silurian (S_3) are shown in figure 19. The Ellsworth Shale is in the Upper Devonian (D_3) and is, therefore, stratigraphically too low in the section. The east-west seismic profiles in this area do not show anything unusual in terms of subsurface collapse structures as proprosed by Hough (1967). It seems more likely that these particular samples were glacial erratics transported from the east as the last glacial lobe was diverted by the Mid-Lake High to a westerly direction.

The bedrock topography east of the S_2S_3 contact and north of Sheboygan shows a gradual increase in roughness. North of Ludington, Michigan, on line QR of the Stone and Webster Engineering Corporation (1979) Survey, the subsurface topography has more relief and the amount of relief continues to increase until the ridge and valley topography is encountered in the North Manitou Island area. An example is shown on the profiles in Figure 20. With the exception of some filling in the valleys, the bedrock is covered by only

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Figure 20.--Near Here

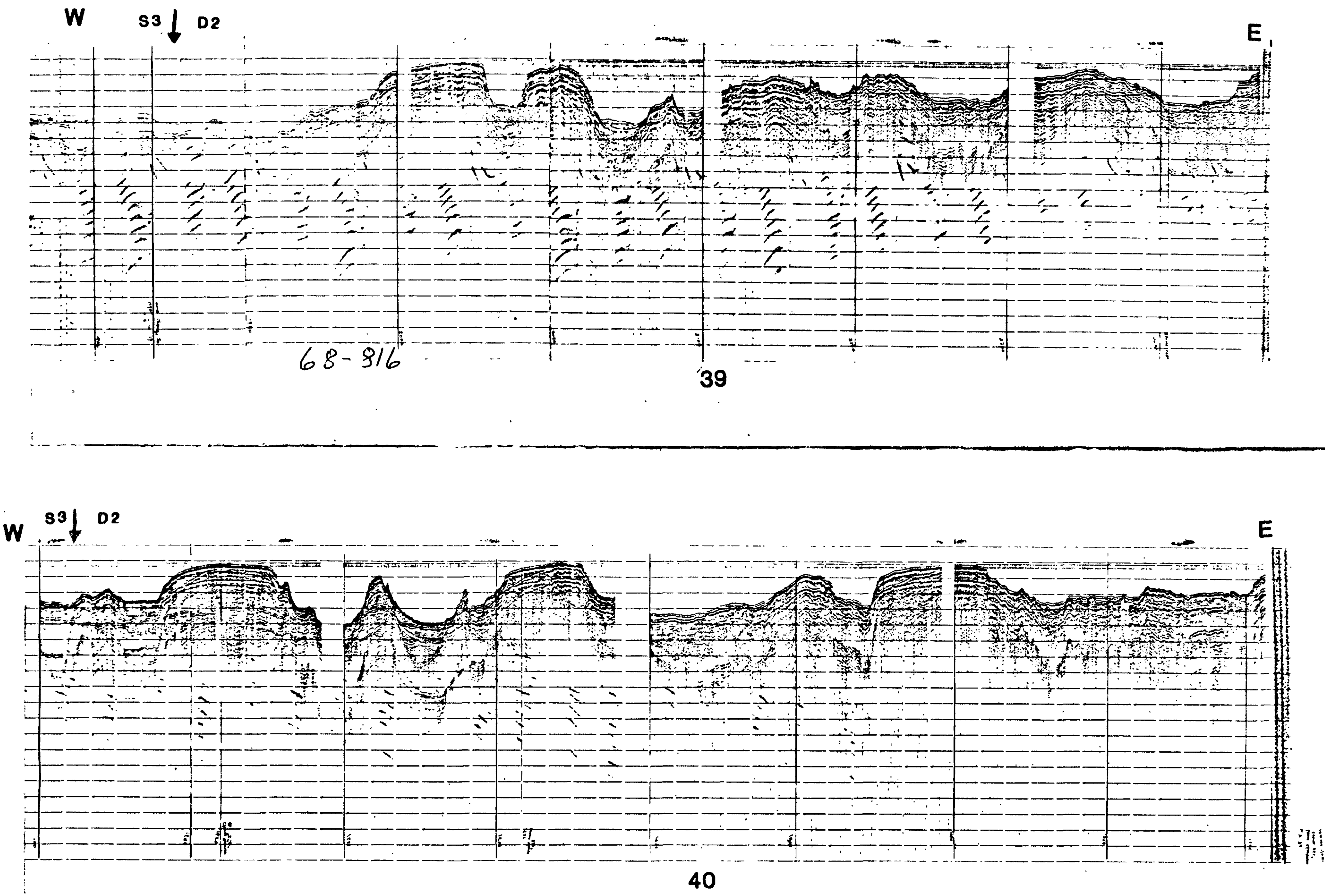

Figure 20.--East-west seismic profiles 39 and 40 in northeast Lake Michigan (see fig. 4).

a few meters of lacustrine sediments.

Mesolella and Weaver (1975) outlined an area in southwestern Michigan, near Muskegon, of salt-collapse structures that have been particularly good traps for hydrocarbons. The stratigraphic units known to contain these structures are shown to extend just off the western Michigan shoreline between Muskegon and Ludington. The seismic data, however, do not show any irregular bedrock features with the exception of a feature about 15 km west of Little Sable Point. This feature (fig. 9) emphasizes a major difficulty of single-channel seismic-reflection data, which is the lack of velocity control. The velocity information can, however, be obtained from multichannel seismic data. As shown in figure 9, the profile seems to indicate at least one and possibly two faults in the eastern part of the profile with a bathymetric difference of 35 m at point A. The velocity information obtained with the multichannel seismic data (Stone & Webster Engineering Corporation, 1979) in the same area indicates a high-velocity till (2400 m/sec) to the left of A on figure 9 overlying Paleozoic basement rock with a velocity of 5500 m/sec. To the right of point A, a lacustrine sediment (1600 m/sec) overlies a different till unit with a velocity of 2100 m/sec over bedrock. The net effect is a much larger apparent basement offset than actually exists. This, in combination with the vertical exaggeration on the record of about 40:1, makes the data look like a possible fault instead of two different age till units adjacent to each other. Apparently the salt leaching and associated collapse structures discussed by Mesolella and Weaver (1975) are limited to the zone between S_2S_3 and D_2D_3 contacts, as Hough (1958) described. As shown in figure 19 the D_2D_3 contact, which would be the upper surface to these collapse features, occurs just off the western shoreline in western Lake Michigan. Therefore, the areas of the lake where salt collapse features may be a potential hazard (fig. 21) are restricted to a northeast-

Figure 21.--Near Here

trending zone offshore from Sheboygan east of the S_2S_3 contact (fig. 19) and including the onshore areas from Frankfort through the Straits of Mackinac west of the D_2D_3 contact shown in figure 19.

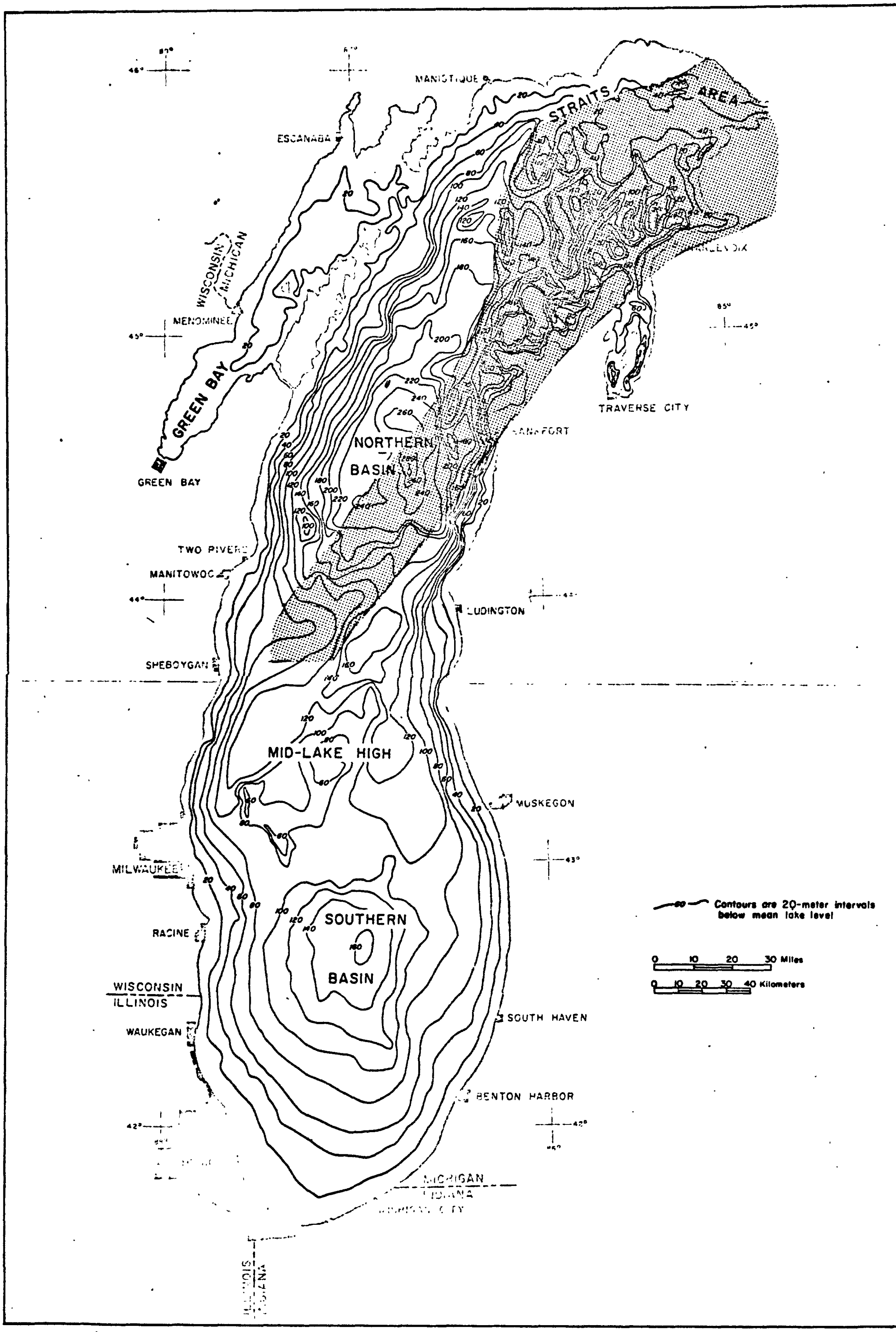

Figure 21.--Shaded zone outlines area that is most likely to have salt collapse features. Bathymetry from Wickham and others (1978).

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